Journal of Irrigation and Drainage Engineering

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--Manuscript Draft--

Manuscript Number:	IRENG-7240R2
Full Title:	Assessing field and laboratory calibration protocols for the Diviner2000 probe in a range of soils with different texture
Manuscript Region of Origin:	ITALY
Article Type:	Technical Paper
Manuscript Classifications:	91.10000: Water Resources Planning & Management; 91.14000: Drought management; 91.44000: Ecological aspects; 95: Hydrology/Hydraulics interface Methods (e.g., artifical neural networks, etc.); 97.20000: Irrigation Hydrology; 99: Technology & Applications; 97.23000: Water Balance
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Assessing field and laboratory calibration protocols for the Diviner2000 probe in a range of soils with different texture

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Abstract

Frequency Domain Reflectometry (FDR) down-hole sensors have been increasingly used for soil moisture field monitoring, because they allow measurement, even continuously, along a soil profile; moreover, they can also be installed with a minimal soil disturbance around the access tube.

Objectives of the paper were to assess field and laboratory calibration protocols for a FDR capacitance probe (Diviner2000) for a range of soils characterized by different particle size distribution and shrink/swell potential, as well as to propose a practical and effective protocol based on undisturbed soil samples accounting for soil shrinkage/swelling processes characterizing swelling clay soils.

Experiments showed that on coarse-textured soils, field calibration under wet, moist and dry conditions, allows estimations of volumetric soil water content with Root Mean Square Error values always lower than 0.058 $cm^3\ cm^{-3}$. On the contrary, the problems occurring in the field on the finer-textured soils, characterized by a clay content ranging between 36.7% and 45.1% and moderate to high shrink/swell potential, did not permit to identify suitable calibration equations and then accurate estimations of soil water content. For such soils in fact, it was observed a great dispersion of the experimental data and consequently high errors values associated to the site-specific calibration equations, up to 0.121 cm^3 cm^{-3} for the soil characterized by the highest clay percentage.

The laboratory experiments were carried out by using undisturbed soil monoliths that, compared to sieved soils, have the advantage to account for the natural soil structure surrounding the access tube, as well as to monitor, during sensor calibration experiments, the soil shrinkage processes occurring in clay soils. The Diviner2000 calibration equations obtained in laboratory were characterized by errors values generally lower then those obtained in the field and always smaller than 0.053 cm^3 cm^{-3}.

Finally, in the range of soil water content between about 10% and the maximum observed, the scaled frequency measured by the sensor resulted almost constant at decreasing soil water content. This circumstance can be ascribed to the normal phase of the shrinkage process determining a compensative effects between the reduction of volumetric soil water content and the increasing soil bulk density. The maximum variations of scaled frequency were observed in the range of soil water content for which soil bulk density resulted approximately constant. The knowledge of soil shrinkage characteristic curve assumes therefore a key-role when calibrating FDR sensors on shrinking/swelling clay soils.

Keywords: Frequency Domain Reflectometry (FDR); Capacitance probe; soil water content; dielectric permittivity; shrinking/swellings soils; calibration protocols.

Introduction

During the last decade, Frequency Domain Reflectometry (FDR) sensors have been largely used as equipment for indirect measurements of soil water content (SWC) as they allow, if compared to traditional methods, easy and non-destructive evaluations (Fares and Alva, 2000). Mazahrih et al. (2008) underlined the importance of soil moisture sensors operating in plastic access tubes inserted in the soil (down-hole soil moisture sensor) for eco-hydrological research and/or for precision irrigation scheduling. Compared to other soil moisture sensors, down-hole sensors have the advantage to be installed with a minimal disturbance of the soil around the access tube, being not necessary to excavate any soil pits, as well as to measure SWC along a soil profile. However, the access tubes can be installed only in case of soils with no rocks and/or stones.

Among the down-hole FDR sensors, Diviner2000 (Sentek Environmental Technologies, 2001) is a handheld soil water content monitoring device, consisting of a portable display/logger unit connected to an automatic depth-sensing probe in which two electric rings, forming a capacitor, are installed at its extremity. The capacitor and the oscillator represent a circuit generating an oscillating electrical field, that propagates into the soil medium through the wall of the access tube. A schematic view of the probe, for field and laboratory calibration, is shown in fig. 1a,b. The sensor's output is represented by the circuit resonant frequency (raw count), *F*, depending on the dielectric properties of the soil surrounding the access tube, variable in a range from ~240 to ~330 MHz, which includes the range from ~250 MHz in saturated soil to ~287 MHz in air-dry soil (Evett et al., 2006). The Enviroscan probe (Sentek Environmental Technologies, 2001) uses the same access tube, but it consists of an array of identical sensors placed permanently at fixed depths and offers the advantage of logging both time and depth series of soil water content.

Figure 1

It has been demonstrated that 99% of the sensitivity is within a radius of 10 cm from the sensor axes (Paltineanu and Starr, 1997), whereas about half of its sensitivity depends on soil water content in the annular region having thickness ranging between 1 and 2 cm around the surface of the access tube. This last circumstance, however, makes the instruments very sensitive to inconsistencies caused by incorrect installation, resulting in air gaps beside the access tube.

The resonant frequency detected by the sensor in the soil (F_s) is scaled to a value SF, ranging between 0 and 1, based on the frequency readings obtained after placing the access tube in air (F_a) and in water (F_w):

$$SF = \frac{F_a - F_s}{F_a - F_w} \qquad (1)$$

The volumetric soil water content, θ [cm^3 cm^{-3}] can be then evaluated by solving the calibration equation, which is usually expressed as:

$$SF = a\ \theta^b + c \qquad (2)$$

where a, b and c are fitting parameters. Specifically for Enviroscan, the default equation initially proposed by the manufacturer and derived from an average of three different Australian soils (sands, loams and clay loams), was characterized by a=0.1957, b=0.404 and c=0.0285 and R^2=0.974 (Sentek Environmental Technologies, 2001), being θ expressed as a percentage of apparent soil volume.

Several Authors stated that the additive constant of eq. (2) can be assumed equal to 0 (Morgan et al., 1999; Geesing et al., 2004; Groves and Rose, 2004; Gabriel et al., 2010); in fact, considering that for θ tending to 0, the corresponding SF values suddenly decrease, for practical applications the related errors can be neglected. The default equation valid for Diviner2000 was obtained under the latter hypothesis, with values of fitting parameters equal to a=0.2746, b=0.3314 (R^2=0.9985). However, the calibration equation proposed by the manufacturer cannot provide accurate measurements of volumetric soil water content for all the soil types, considering that the soil dielectric properties are affected by soil texture and structure. Moreover, agricultural activities also play a significant impact on soil properties like bulk density and organic matter content, so affecting its water storage capacity. Site-specific calibration equations have been therefore largely recommended in order to obtain accurate values of actual volumetric soil water content (Paraskevas et al., 2012; Evett et al., 2006).

In the last two decades numerous experiments have been carried out in field and in laboratory to identify site-specific calibration equations for Enviroscan and Diviner2000 sensors on soils characterized by different texture, as well as to evaluate the effects of soil salinity and temperature on the performance of the sensors. Among the first, Mead et al. (1995) presented the calibration and sensitivity analysis of Enviroscan probe to salinity and bulk density changes, related to three soil types (coarse sand, sandy loam with two bulk densities and clay soil). The sensor calibration, carried out under controlled laboratory conditions, showed significant differences even within the two sandy loam soils, which only differed in bulk density. Morgan et al. (1999), using the Enviroscan probe and the default calibration equation on three sandy soil collected in Florida, USA, observed the underestimation of soil water content, when the default calibration equation was used.

Alternatively, in shrinking/swelling clay soils, a comparison between Diviner2000 and neutron probe was carried out by Burgess et al. (2006). These Authors indicated that the site-specific calibration equations obtained for both the sensors were substantially different from the default equation even if, after a field calibration the two instruments gave similar estimates of change in soil water content integrated over a meter depth. Even Gabriel et al. (2010), based on field and laboratory measurements with the Enviroscan probe on loamy soils, determined calibration equations characterized by satisfactory coefficients of determination (R^2=0.96 and R^2=0.92, respectively), whose fitting parameters however resulted significantly different than those characterizing the default equation.

Based on experimental data acquired on laboratory columns filled with three different soils (silt loam, loam and clay), Evett et al. (2006) obtained calibration equations for Diviner2000 and Enviroscan characterized by high coefficient of determinations (R^2>0.99) and RMSE of the order of 0.02 $cm^3\ cm^{-3}$, even if in a previous field calibration of Diviner2000 on two Austrian soils (silty clay loam and silt loam), Evett et al. (2002) presented lower R^2 (R^2=0.533 and 0.416) and higher RMSE (RMSE=0.038 and 0.046).

According to Paltineanu and Starr (1997), the accuracy of field calibration equation depends on errors related to the sampling of the soil volume investigated by the sensor, that must be done accurately. Moreover, in swelling/shrinking soils, the changes of soil bulk volume with soil water content causes modification in the pore geometry, as indicated by the bulk density-soil water content relationship (soil shrinkage characteristic curve). The coefficient of linear extensibility, *COLE*, (Grossmann et al., 1968; Franzmeier and Ross, 1968), derived by bulk densities of soil clods or undisturbed samples, is generally used for quantifying soil shrink/swell potential. The higher the presence of clay minerals in the smectite group, the greater is the soil shrink/swell potential, whereas illitic clays manifest intermediate shrink/swell potential and kaolinitic clays are least affected by volume changes with soil water content.

Malicki et al. (1996) and Davood et al. (2011) suggested that the changes in soil bulk density must not be disregarded when calibrating capacitance sensors. Even Fares et al. (2004), based on field experiments, estimated errors in volumetric soil water content up to 20% when ignoring the variations of soil bulk density.

On the contrary, based on laboratory experiments aimed to calibrate the ThetaProbe type ML1 (Delta-T Devices, Cambridge, England) on a clay loam soil, Lukanu and Savage (2006) observed a negligible influence of the variations of clay content, soil bulk density and soil temperature detected at different investigation depths, on measured soil water content. Actually, soil bulk density has to be considered a source of uncertainty in volumetric soil water contents estimation, because it influences soil dielectric permittivity (Gardner et al., 1998) and governs the relationship between gravimetric and volumetric soil water contents (Geesing et al., 2004).

Hignett and Evett (2008) underlined that the default calibration equation has to be performed in a temperature-controlled room, by using distilled water and homogeneous soil materials (loams or sands), uniformly packed around the sensor. Even if the suggested procedure addressed to a very accurate calibration, the resulting equation cannot be extended to the common field conditions.

Despite the manufacturers recommendation to use the default calibration equations to monitor the “relative soil water status”, the need of site-specific calibration arises when actual soil water content is monitored for irrigation scheduling (Evett et al., 2011). The review of Robinson et al. (2008) has recently proposed to consider soil water content as an environmental variable, which should be monitored and shared in common databases aimed to assume a global awareness of the different water-controlled phenomena. With this in mind, the actual values of soil water content have to be considered so that, when using a certain sensor, it is crucial to achieve its highest accuracy.

Moreover, the need to standardize methodologies and techniques for laboratory and field calibration of electromagnetic (EM) soil water sensors, has been recently emphasized by Paltineanu (2014) during the Fourth International Symposium on Soil Water Measurement using Capacitance, Impedance and Time Domain Transmission (TDT), hold in Quebec, Canada. Experimental protocols for calibration of any soil water content sensor must provide detailed information describing the sensor’s physical response to the system (operation frequency, response to air and distilled water at ~22 °C, room temperature, axial and radial sensitivity of the sensor in distilled water, in air–water and in air–soil interfaces), the soil intrinsic characteristics (texture, clay mineralogy, electrical conductivity, organic matter, gravel content, coefficient of uniformity for bulk density in the soil volume investigated by the sensor). Additionally, the common use of statistical analysis and data interpretation was finally advocated. Even if copious literature exists on FDR sensor calibration for different soils, the lack of a site-specific calibration equation for Sicilian soils in which other researchers are ongoing (Cammalleri et al., 2013; Provenzano et al., 2013; Rallo et al., 2012; Rallo et al., 2014), as well as the requirements of standardizing the calibration protocols, indicated the need to pursue the following objectives: i) to assess field and laboratory protocols to calibrate a Diviner2000 capacitance probe on seven irrigated soils of Western Sicily characterized by a different texture and shrink/swell potential; ii) to analyze their performance and to propose a practical and effective protocol of sensor calibration, based on undisturbed soil samples.

Materials and Methods

Experiments were carried out on seven different soils collected in the five irrigated areas of Western Sicily shown in fig. 2, representative of different textural classes. Sampling sites were chosen according to the variability of soil particle distribution and containing limited gravel content, a low salinity and a low amount of organic matter. Only for the site of Castelvetrano (CAS), two different locations were investigated: the first (CAS-A) was located in an area characterized by a coarse-textured soil, whereas the second in an area with higher clay content. For the latter, two different soil layers, i.e. 0-30 cm and 60-90 cm, were investigated (CAS-B, CAS-C).

Figure 2

Disturbed soil samples were used for the preliminary particle size analysis as well as to evaluate the gravel content and the soil electrical conductivity. Particle size distribution was determined by coupling a sieving column and the Bouyoucos hydrometer (ASTM 152H). The textural classes were defined according to the USDA classification system (Soil Survey Division Staff, 1993). For each soil sample, the amount of skeleton [g kg^{-1}] was determined by dividing the weight [g] of the material held by a 5 mm sieve, to the dry weight [kg] of the original sample from which it was extracted (Pagliai, 1998).

The retained material was washed with a Calgon solution (sodium hexametaphosphate), dried in an oven at 105 °C for 48 hours and finally weighted.

Soil electrical conductivity, *EC*, was determined on the soil-water extract 1:5 with a conductivity meter (CRISON, microCM 2200) by following the standard procedure presented in Pagliai (1998). For each site, the calibration equation for the Diviner2000 capacitance probe was determined by following the standard field procedure, as suggested in the user's manual, as well as by using a laboratory procedure on undisturbed soil samples, as following described in detail.

Field calibration

Field calibration took place in 2013, during measurement campaigns carried out in three different periods of the year, with the aim to explore a relatively wide domain of soil water contents (wet, moist, dry). The first measurement campaign was generally carried out after significant rainfall events, so that the soil water status was approximately close to the field capacity. The second campaign was accomplished when soil water contents ranged between 0.15 cm^3cm^{-3} and 0.25 cm^3cm^{-3}, while the third was completed at the end of the dry season, for soil water contents lower than about 0.15 cm^3cm^{-3}.

For each selected site, six PVC access tubes (length of 0.35 m) were installed in three groups consisting of two, that were investigated in pairs, during each measurement campaign. To avoid interference, the distance between each group of access tubes was 0.30 m, whereas the distance between the pairs was 0.50 m. Access tubes were installed with the specific kit, to reduce the soil disturbance during installation and to ensure the perfect contact between soil and tube, in order to avoid air gaps and preferential water flow.

During each measurement campaign, values of scaled frequency (*SF*) were initially acquired by placing the sensor in air and in water and then in both the access tubes, with a 5 cm step, from 5 cm to 25 cm depths. To reduce the measurement errors, scaled frequencies were acquired during the descent and the ascent of the sensor into the tube, and then averaged at each single depth. After the measurements, twelve undisturbed soil samples (8.0 cm diameter and 5.0 cm height), at four distinct soil depths (0-5 cm, 5-10 cm, 15-20 cm and 25-30 cm) were collected around each access tube. Immediately after collection, soil samples were leveled, cleaned and weighed (accuracy of balance 0.01 g). Samples were then oven-dried at 105 °C for 48 h, weighted and finally sieved to determine, for each of them, the skeleton content, gravimetric water content, soil bulk volume and finally volumetric water content. Values of soil bulk volume were corrected to accounting for the amount of skeleton identified in the sample, as suggested by Cavazza (2005).

Laboratory calibration

Laboratory calibration was carried out on undisturbed soil monoliths, having diameter and height equal to about 0.25 m, in which contemporary measurements of scaled frequency (*SF*), gravimetric soil water content (*U*), and the corresponding soil bulk density (ρ_b) were carried out, so to cover the range from field capacity to oven-dry. The dimensions of soil samplers were chosen according to the sensing volume investigated by the sensor, so that about 99% of the sensor response was controlled by the soil inside the monolith.

For all the investigated sites, two samples were collected after extensive rainfall events, when soil water content was close to the field capacity, to avoid re-wetting the soil before starting the experiment. The photographic sequence in fig. 3a,i shows the different phases of sampling: soil surface was leveled (fig. 3a) before inserting a 0.30 m long access tube. To ensure verticality, a wood guide and a level were used during installation (fig. 3b,d). Once installed (fig. 3e), the access tube was cleaned inside and the sampler positioned in a way to set the access tube in its axial position (fig. 3f). A hammer was used to gradually tap the sampler in the soil (fig. 3g). Finally, the soil sample was carefully removed (fig. 3h,i), wrapped in a plastic film, sealed and transported to the laboratory.

Figure 3a,i

Scaled frequency and the corresponding weight of the sample were measured during an air-drying process, initially on a daily frequency, which was later reduced according to the water lost.

At the same time, the apparent volume of soil monolith was monitored in order to consider the possible shrinking processes characterizing the soils containing swelling clay (Crescimanno and Provenzano, 1999). Vertical subsidence of the soil surface was measured on eight marked positions chosen along two orthogonal directions, with a precision Vernier caliper (accuracy 0.1 mm) bolted to a bar, allowing bi-dimensional movements. A micro-switch, glued to the shaft of the caliper, was activated by contact with the soil surface. For each soil water content, the sample height was then obtained by considering the arithmetic mean of the eight values. The sample was then oven-dried and finally its weight and height re-measured. After oven drying, the PVC sampler was removed and the circumference of the core measured, with a flexible tape (accuracy 0.5 mm), at three different heights.

The latter measurement allowed to determine the geometrical factor (Bronswijk, 1990), that was assumed valid for the whole shrinking process, which accounts for the relative amount of vertical contraction caused by the change of the sample volume. Based on these measurements it was possible to determine the soil bulk volume corresponding to each measured gravimetric water content, the soil bulk density and finally, the volumetric water content.

The knowledge of soil bulk volumes at field capacity, V_{wet}, and after oven-drying, V_{dry}, allowed to quantify the shrink/swell potential of investigated soils according to the coefficient of linear extensibility, *COLE*, evaluated as (Grossman et al., 1968):

$$COLE = \left(\frac{V_{wet}}{V_{dry}}\right)^{1/3} - 1 \qquad (3)$$

Statistical Analysis

The knowledge of volumetric water contents and the corresponding scaled frequencies allowed to fit the calibration equation, represented by the exponential regression of eq. 2, assuming c=0. According to Geesing et al., (2004), even though *SF* is the dependent variable, it was considered as the independent variable, because the equation application is aimed to derive the volumetric water content, θ, from the scaled frequencies *SF*, provided by the sensor. The exponential regression was obtained on both field and laboratory data, using SYSTAT 13 (Systat, 2014) for nonlinear regression, whose output also provides the coefficient of determination (R^2) and the Root Mean Square Errors (RMSE).

Results and Discussion

Figure 4 shows the particle size distributions for the examined soils, indicating the extremely high variability that characterizes them. Tab. 1 summarizes the percentage of clay, silt, sand and soil textural class (Soil Survey Division Staff, 1993), as well as the content of skeleton, the percentage of organic matter (OM) and the values of soil electrical conductivity ($EC_{1:5}$). As can be observed, according to clay and sand contents, whose values ranged respectively from 9.1% to 45.1% and from 17.3% and 85.8%, the soils cover different textural classes. According to the percentage of skeleton, variable between 2 e 72 g kg^{-1}, samples can be considered very slightly (<30 g/kg) or slightly stony (30-150 g/kg) (Boden, 1994); based on soil electrical conductivity ($EC_{1:5}$), ranged from 0.11 dS m^{-1} and 0.36 dS m^{-1}, soils can be classified as non-saline (Soil Survey Division Staff, 1993).

Figure 4

Table 1

Field calibration

For the different sites, fig. 5a-g shows the average values of the measured volumetric soil water content, θ, as a function of scaled frequency, SF, measured in the field; the error bars identify the standard deviations of θ, obtained by considering the three undisturbed samples collected at the same depth. Figure 5a-g also illustrates the $\theta(SF)$ relationships suggested by the manufacturer, as well as the experimental regression curves, fitted according to eq. 2, whose coefficients and statistical parameters, indicated in table 2, were obtained assuming the condition of c=0, despite the slight regression improvement associated to an intercept different than zero (Paltineanu and Starr, 1997). Table 2 also indicates the ranges of variability of measured soil water contents and RMSE values associated to both the fitting regression curves and the default calibration equation.

As can be observed in fig. 5a-g, for the three coarser-textured soils (PAR, CAS-A and MAR), despite the relatively high dispersion of the experimental data, the empirical $\theta(SF)$ relationships obtained in the field resulted very close to the one proposed by the manufacturer, as demonstrated by the similar RMSE values, indicated in table 2. The relatively good performance associated to the default equation (RMSE$\leq$0.08 cm^3 cm^{-3}), confirms the general validity of this equation for coarse-textured soils, even if the site-specific calibration equation get to a general improvement of soil water content estimations.

On the contrary, for the finer-textured soils (CAS-B, PIN and SAL), it was not possible to determine reliable calibration equations, mainly because of soil cracking observed in the field.

Figure 5a-g

Table 2

The occurrence of shrinking processes in the finer-textured soils could have determined, even during the second measurement campaign, the opening of cracks in the soil volume investigated by the sensor. This circumstance was particularly evident for the soil PIN, for which the loss of contact between soil and the access tube was visible with the naked eye when the soil was dry, making it impossible to collect any consistent data. For this soil therefore, despite the high R^2 (R^2=0.87) and the low RMSE (RMSE=0.042) obtained, considering the limited number of reliable data acquired, the fitted equations cannot be considered appropriate for the whole range of SWCs occurring in the field (fig. 5f).

A different problem took place in CAS-C site where, in relation to the investigated soil layer (60-90 cm), the variations of soil water content were quite limited, with values of θ that never decreased below 20%. A similar behavior was observed by Fares et al. (2004) on a clay subsoil, in which the minimum soil water content, measured in the field, resulted equal to 18.3%. In this case, it was not possible to identify a calibration equation valid for a wide range of soil water contents (fig. 5e).

For the three coarser-textured soils, the default calibration equation generally underestimates the measured volumetric water content when the scaled frequency assumes values lower than about 0.85 and overestimate θ in the other cases. Geesing et al. (2004) on a silt-loamy soil and Polyakov et al. (2005) on silty-clay-loam and clay-loam soils observed that the default calibration equation generally overestimates θ. According to the RMSE values associated to the default calibration equations indicated in table 2, it is noteworthy that in finer-textured soils values of RMSE tend to increase at increasing clay content, reaching values even higher than 0.10 $cm^3\ cm^{-3}$.

Figure 6a-g shows the values of soil bulk density, ρ_b, and gravimetric water content, U, determined on soil cores collected around the access tubes, as a function of sampling depth. As it can be noticed, the average bulk density, increasing at increasing depth in the layer 0-30 cm, is in general characterized by a greater variability in the top-layers compared to the deeper layers; moreover, for each fixed depth, a quite high variability is also evident on gravimetric water content. Even Paltineanu and Starr (1997) underlined the great variability associated to both soil bulk density and gravimetric water content, making it difficult, therefore, to obtain low RMSE values in the field.

Figure 6a-g

The spatial variability observed on ρ_b and U could be associated to the sampled soil volume, not representative of the fringe volume investigated by the sensor, whereas the temporal variability can be a consequence of the different soil bulk density with soil water content at sampling, associated to the presence of swelling clays.

Similar results were found by Paltineanu and Starr (1997) who discussed about the difficulties of getting accurate field measurements of ρ_b and θ in the fringe volume investigated by the sensor, indicating that more accurate calibration equations can be obtained under more controlled laboratory conditions, where it is possible to minimize the uncertainties associated to the field measurements.

Laboratory calibration

Since the publication of the manufacturer's user manual (Sentek Environmental Technologies, 2001), several investigations have been carried out regarding FDR sensors under laboratory conditions. Paltineanu and Starr (1997), Gabriel et al. (2010), Haberland et al. (2014), Rallo and Provenzano, (2014), presented site-specific calibration equations obtained on soil samples prepared in laboratory, by using soils with different texture and sieved through a 5 mm mesh.

The laboratory calibration procedure proposed here refers to undisturbed soil monoliths, in order to account for the natural soil structure surrounding the access tube, as well as for the possible variations of apparent soil volume due to the presence of swelling clay. Using such monoliths in fact, allows the contextual monitoring of gravimetric water content, U, soil bulk density, ρ_b, as well as the sensor scaled frequency, *SF*, during an air-drying process of soil sample. Using undisturbed monolith represents a substantial improvement of field calibration method listed above.

For the different examined soils, table 3 shows the maximum gravimetric water content measured immediately after sampling, U_{max}, the minimum and maximum bulk density, ($\rho_{b,min}$, $\rho_{b,max}$), as well as the coefficient of linear extensibility, *COLE* and the skeleton content, *S*. Minimum ρ_b corresponds to the maximum soil water content at sampling, equal approximately to field capacity, whereas maximum ρ_b corresponds to the oven-dry condition. According to the *COLE* values, investigated soils showed shrink/swell potential ranged from low (COLE<0.03) to high (0.06<COLE<0.09) (Parker et al., 1977). Similarly to what determined on the smaller samples (8.0 * 5.0 cm), based on the skeleton content, the considered soils are very slightly or slightly stony.

Table 3

The ratio between the highest and the lowest bulk density, associated to the maximum variations of soil bulk volume, varied from values slightly higher than 1.0 on coarse-textured soils to 1.25, obtained on the sample SAL, containing the highest clay percentages. Moreover, it is noteworthy that this ratio, as well as the *COLE* values, tend to increase at increasing clay content, confirming the presence of swelling clay in the samples. As known, in fact, a value of the ratio equal to 1.0 is typically associated to rigid soils, whereas higher values are usually obtained on shrinking soils.

Figure 7a-g shows, for the different soils, the values *θ, SF* obtained on both the monoliths and the corresponding fitting regression curves, whose coefficients and statistical parameters (R^2 and RMSE) are indicated in table 4. As can be noticed on fig. 7a-g, a limited dispersion of experimental points around the fitting curve was found only for the finer-textured soils, being practically absent for the others, confirmed by R^2, higher than 0.84 and RMSE values, always lower than 0.053 $cm^3\ cm^{-3}$.

Figure 7a-g

Table 4

Moreover, for the finer-textured soils and at the highest *SF* values, significant variations of θ corresponded to limited changes of *SF*. This circumstance can be ascribed to the effects of increasing bulk density, observed at decreasing water content, on the soil dielectric permittivity; in fact, mainly during the initial phase of the drying process, any reduction of soil porosity changes the mutual proportions of water, air and solid particles, so affecting the soil dielectric permittivity and consequently the resonant frequency, F_s, detected by the sensor. As observed by Davood et al. (2012), for a fixed water content, there exists a positive linear relationship between soil dielectric permittivity and soil bulk density, as a consequence of the higher mass of solid particles per unit soil volume. In other terms, the almost constant *SF* values depend on the combined effect between the reduction of soil water content and the contextual increase of soil dielectric permittivity. Other possible explanations for this behavior were provided by Evett. et al. (2008), who referred how capacitance sensors are influenced by some properties of the soil–water system around the access tube and not only by the water content. Such properties have been related to the soil structure and to the non uniform penetration in the soil of the electromagnetic field generated by the sensor (Evett and Steiner, 1995), as well as to the distortion of the electromagnetic field generated by the individual arrangement of soil peds and by the pattern of water content in the peds around the access tube.

In order to exclude the effects of variations of bulk density on volumetric soil water content, *SF* values were then represented as a function of the gravimetric water content, *U*, rather than θ. For the different soils, fig. 8a-g shows, as a function of *U*, the values of scaled frequency, *SF* (main axes) and of soil bulk density, ρ_b (secondary axes), obtained on both the monoliths. As known, the relationship $\rho_b(U)$ represents the soil shrinkage characteristic curve.

Figure 8a-g

By observing fig.8a-g, it can be noticed that the values of soil bulk density resulted quite different between the soils, which particularly manifested a quite dissimilar behavior and exhibited, in several cases, extensive variations of ρ_b in the range of investigated U, as a consequence of the shrinking processes occurred in the samples.

Except that for the coarse-textured soils (PAR, CAS-A and MAR) characterized by the absence or limited soil shrinkage ($COLE$<0.03), for the other samples very limited variations of SF occurred in the range of gravimetric soil water contents higher than a certain threshold value ($U^* \approx 0.10$ g g^{-1}). This threshold represents roughly the lower limit of the normal phase of the shrinking process, in which the variations of soil bulk volume are approximately proportional to the gravimetric water content U. For gravimetric water content smaller than the threshold, it can be noticed that the variations of soil bulk density are limited or absent (residual phase of soil shrinkage characteristic curve) and, at the same time, the most significant variations of sensor scaled frequency occur.

Similarly to what observed on the $\theta(SF)$ experimental data pairs for finer-textured soils, even the $SF(U)$ data showed analogous behavior, considering that only in correspondence of the residual phase of the shrinking process ($U<U^*$; ρ_b = constant), SF values tend rapidly to increase at rising U; otherwise, variations of SF tend gradually to reduce at increasing U, during the normal phase of the shrinkage process ($U> U^*$ and $\rho_b = f(U)$), up to be absent at the highest water contents.

Soil contraction, in fact, determines changes in bulk soil permittivity, ε_b, depending on the rates of water, air and solid matrix in the fringe volume investigated by the sensor. At the beginning of shrinkage process, the relatively small reduction of *SF* at decreasing *U* can be attributed to the circumstance that the variations in water content are in whole or in part compensated by the changes of soil bulk density. In other words, as shown by Gong et al. (2003) and more recently by Davood et al. (2012), this behavior is caused by the increase of the solid particles per unit of soil volume and consequently by the higher contribution of the soil permittivity, since the solid particles are characterized by values of dielectric constant higher than the air.

Conclusions

In this paper, field and laboratory calibration equations for Diviner2000 capacitance probe were assessed and a practical and effective protocol for sensor calibration proposed. Experiments considered seven Sicilian irrigated soils characterized by different textures classes and shrink/swell potential, quite limited content of skeleton, as well as low values of soil electric conductivity.

The results of field calibration, carried out by using the procedure suggested by the manufacturer under wet, moist, and dry conditions, indicated that for the three coarser-textured soils the default calibration equation can be considered valid, resulting in RMSE values associated to estimated volumetric soil water content, θ, always lower than 0.080 $cm^3\ cm^{-3}$. However, for these soils the site-specific calibration equation improved the estimation of θ, as confirmed by the systematic reduction of RMSE to values always lower than 0.058 $cm^3\ cm^{-3}$.

For the finer-textured soils, instead, some problems occurred in the field during the sensor calibration, because of the presence of swelling clays, making the field calibration not reliable for these soils. In fact, soil shrinkage processes occurring under the driest examined condition and visibly evident for the soil PIN, determined the opening of cracks and the presence of air gaps in the fringe volume investigated by the sensor. The loss of contact between soil and access tube, made it impossible to collect any consistent data to be used for sensor calibration. Otherwise, in the site CAS-C, due the investigated soil depth (60-90 cm), it was possible to explore only a limited range of soil water contents, between about 0.20 and 0.30 $cm^3\ cm^{-3}$. For finer-textured soils, RMSE values associated to the site-specific calibration equation resulted generally high, with values up to 0.121 $cm^3\ cm^{-3}$ for the site SAL, characterized by the highest clay percentage. The great dispersion of $\theta(SF)$ data pairs not only resulted as a consequence of changes in soil water content, but also from the observed spatial and temporal variability of soil bulk density in the fringe volume investigated by the sensor. In line with Paltineanu and Starr (1997) therefore, more controlled laboratory conditions for sensor calibration allow minimizing the recognized uncertainties associated to the field measurements. Moreover, compared to tedious and time-consuming field calibration procedure, in laboratory it is possible to explore with continuity a wide range of soil water contents.

Laboratory calibration was carried out on undisturbed soil monoliths that, compared to the traditionally considered sieved samples, have the advantage to account for the natural soil structure. For shrinking/swelling clay soils, using undisturbed soil monoliths allows to monitor the increasing bulk density at decreasing soil water content and to limit the presence of air gaps between the access tube and the surrounding soil, as occurred in the field.

For the considered soils it was observed that the ratio between the highest and the lowest bulk density, corresponding respectively to the oven dry condition and to maximum water content, resulted ranging between 1.0, measured on the rigid sandy-loam soil (PAR) and 1.25, obtained on the shrinking clay soil (SAL), with values basically increasing at increasing clay content. With the laboratory calibration protocol, compared to the field procedure, it was possible to limit the dispersion of the experimental $\theta(SF)$ values around the fitting curve, as confirmed by the general reductions of the corresponding RMSE, whose values never exceeded 0.030 $cm^3\ cm^{-3}$ for coarse-textured soils and 0.053 $cm^3\ cm^{-3}$ for fine-textured soils. For the latters, it was also observed that at the highest *SF*, significant variations of θ were associated to limited changes in the scaled frequency, as a consequence of the effects of shrinkage processes on soil dielectric permittivity and then on resonant frequency detected by the sensor, confirming that capacitance sensors are influenced by properties of the soil–water system around the access tube and not only by the changes in soil water content.

In order to exclude the effects of soil bulk density on soil water content, it was suggested to represent the sensor scaled frequency as a function of gravimetric water content, *U*, rather than volumetric θ, thus to investigate, at the same time, even on the consequences of soil shrinkage processes on *SF*.

Experimental results showed that the values of *SF* rapidly increased at increasing *U* in correspondence with the residual phase of the shrinking process (constant bulk density), to become approximately constant during the normal phase of the shrinking process, in which bulk density is a function of soil water content. In other terms, at relatively high *U*, it was observed that the variations in soil water content were in whole or in part compensated by the changes of soil bulk density, so that the final scaled frequency measured by the sensor resulted approximately constant.

When calibrating FDR sensors on shrinking/swelling clay soils, is then necessary to determine the soil shrinkage characteristic curve whose knowledge, associated to the sensor calibration equation, expressed as *U(SF)*, allows to determine the volumetric water content.

Further investigations are however necessary to identify how the soil shrinkage characteristic curve can be introduced in the sensor calibration equation in terms of $\theta(SF)$, as well as to verify the possibility of indirect estimation of the calibration equation parameters based on easy-to-measure soil physical variables.

Acknowledgements

The research was co-financed from Ministero dell'Istruzione, dell'Università e della Ricerca (www.miur.it) under the project PRIN 2010-2011 and Università degli Studi di Palermo, under the project FFR 2012, both coordinated by G. Provenzano.

The contribution to the manuscript has to be shared between authors as following: Experimental set-up, data processing and final revision of the text have to be divided equally between Authors. Field data collection was cared by G. Rallo. Text was written by G. Rallo and G. Provenzano.

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Figure Caption List

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Tab. 1 –Physical properties of investigated soils

Site	ID	Clay [%]	Silt [%]	Sand [%]	Soil textural class (USDA)	Skeleton [g kg^{-1}]	OM [%]	$EC_{1:5}$ [dS m^{-1}]
Partinico	PAR	9.1	5.1	85.8	S-L	20	n.d.	0.11
Castelvetrano	CAS-A	20.0	16.3	63.7	L-S-C	17	2.0	0.31
Marsala	MAR	24.6	26.9	48.5	L-S-C	32	2.6	0.22
Castelvetrano	CAS-B	38.7	13.4	42.4	L-C	4	1.9	0.18
Pietranera	PIN	37.4	33.8	28.8	L-C	32	2.0	0.35
Castelvetrano	CAS-C	36.7	17.9	45.3	S-C	2	2.0	0.18
Salemi	SAL	45.1	37.6	17.3	C	72	2.0	0.23

Tab- 2 –RMSE associated to the fitting regressions and default calibration equations. The number of measurements, the range of θ and the parameters of eq. 3 are also indicated for the different soils.

ID	**N**	**Range of θ [cm^3 cm^{-3}]**		**Fitting regression equation**				**Default equation**
		min	**max**	***a***	***b***	**R^2**	**RMSE**	**RMSE [cm^3 cm^{-3}]**
PAR	24	0.01	0.37	0.439	2.869	0.84	0.049	0.054
CAS-A	24	0.03	0.30	0.359	2.130	0.76	0.054	0.080
MAR	18	0.08	0.29	0.482	2.650	0.73	0.058	0.063
CAS-B	24	0.05	0.33	0.473	1.709	0.67	0.074	0.100
PIN	16	0.17	0.49	0.453	0.446	0.87	0.042	0.166
CAS-C	27	0.20	0.31	0.347	1.084	0.35	0.040	0.110
SAL	24	0.04	0.33	0.576	2.007	0.49	0.121	0.113

Table 3

Tab. 3 - Values of maximum gravimetric water content (U_{max}), minimum ($\rho_{b,min}$) and maximum ($\rho_{b\ max}$) soil bulk density, coefficient of linear extensibility (COLE) and skeleton content, S, measured on undisturbed soil monoliths

ID	U_{max}	$\rho_{b.min}$	$\rho_{b,max}$	$\frac{\rho_{b\max}}{\rho_{b\min}}$	***COLE***	***S***
	[g g^{-1}]	**[g cm^{-3}]**	**[g cm^{-3}]**	**[-]**	**[-]**	**[g kg^{-1}]**
PAR	0.28	1.50	1.51	1.00	0.000	20
CAS_A	0.27	1.40	1.49	1.06	0.020	21
MAR	0.29	1.31	1.33	1.01	0.003	32
CAS_B	0.17	1.57	1.74	1.11	0.035	4
PIN	0.21	1.40	1.70	1.21	0.066	10
CAS_C	0.20	1.41	1.65	1.17	0.054	3
SAL	0.24	1.32	1.65	1.25	0.077	72

Tab. 4 - Coefficients a and b of eq. 3 and related R^2 and RMSE, obtained on undisturbed monoliths. The total number of experimental determinations, N, on both the samples is also indicated

ID	**N**	***a***	***b***	**R^2**	**RMSE [cm^3 cm^{-3}]**
PAR	38	0.607	5.013	0.94	0.029
CAS_A	45	0.571	5.813	0.93	0.015
MAR	52	0.555	5.127	0.95	0.030
CAS_B	29	0.393	6.590	0.95	0.039
PIN	16	0.282	5.152	0.94	0.044
CAS_C	30	0.534	7.310	0.87	0.053
SAL	59	0.587	10.493	0.84	0.049

Fig1
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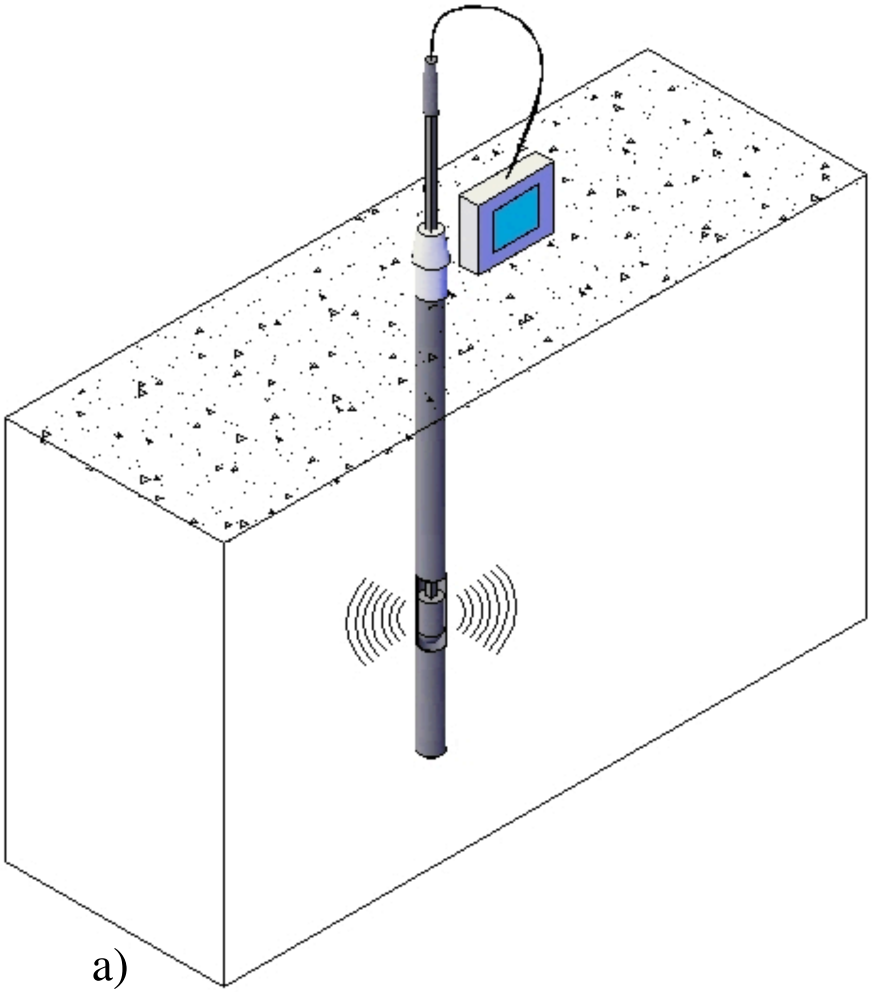

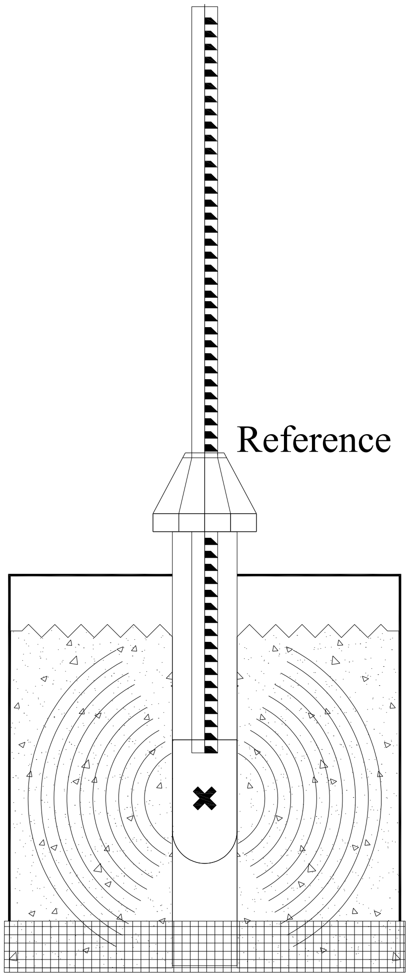

Fig2

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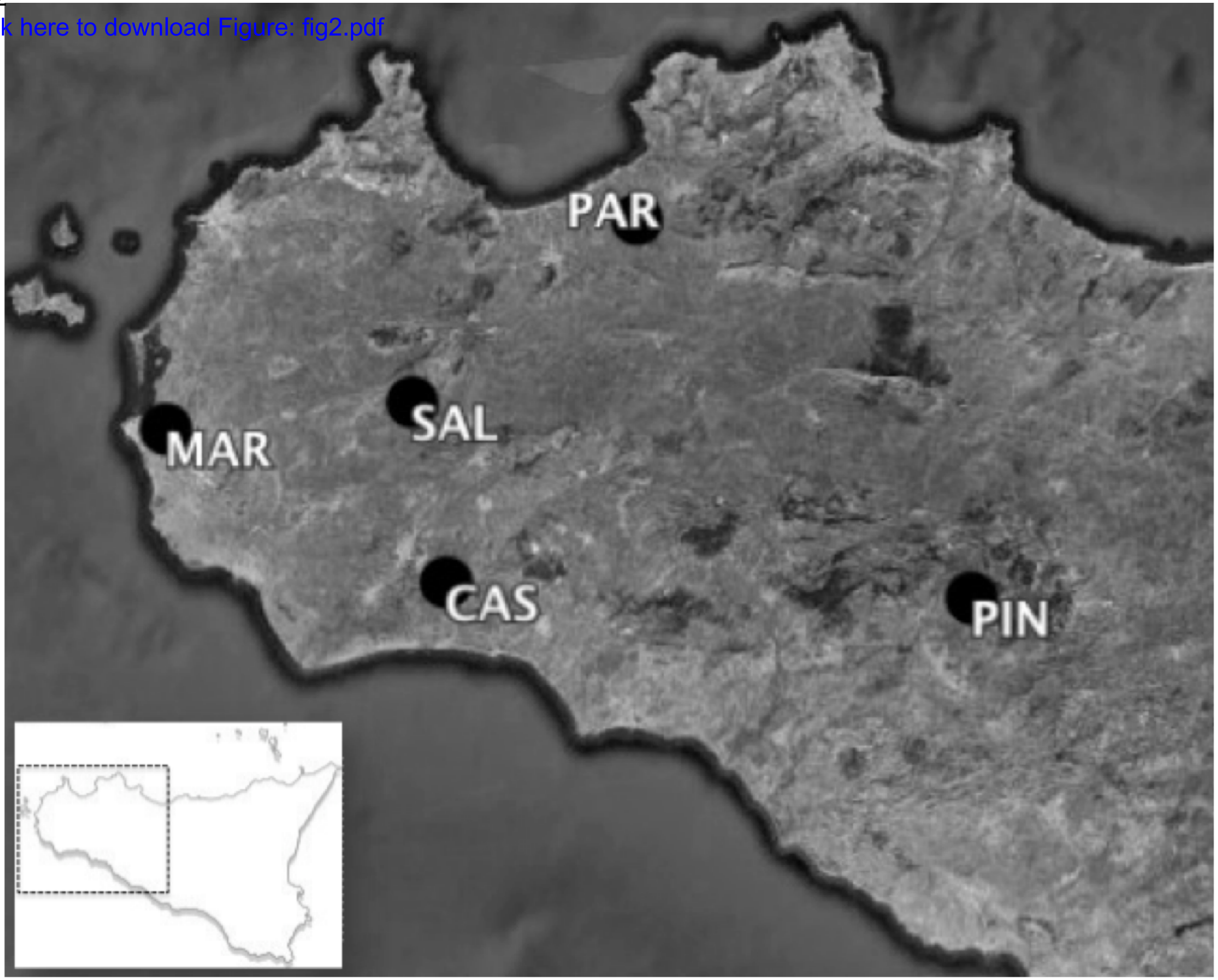

Site	ID	UTM ED50 coordinates [m]	
		East	North
Partinico (PA)	PAR	330516.8	4208994.2
Castelvetrano (TP)	CAS	310086.4	4168408.9
Marsala (TP)	MAR	278561.3	4186111.9
Pietranera (AG)	PIN	367878.4	4165752.0
Salemi (TP)	SAL	305920.6	4188651.2

Fig3

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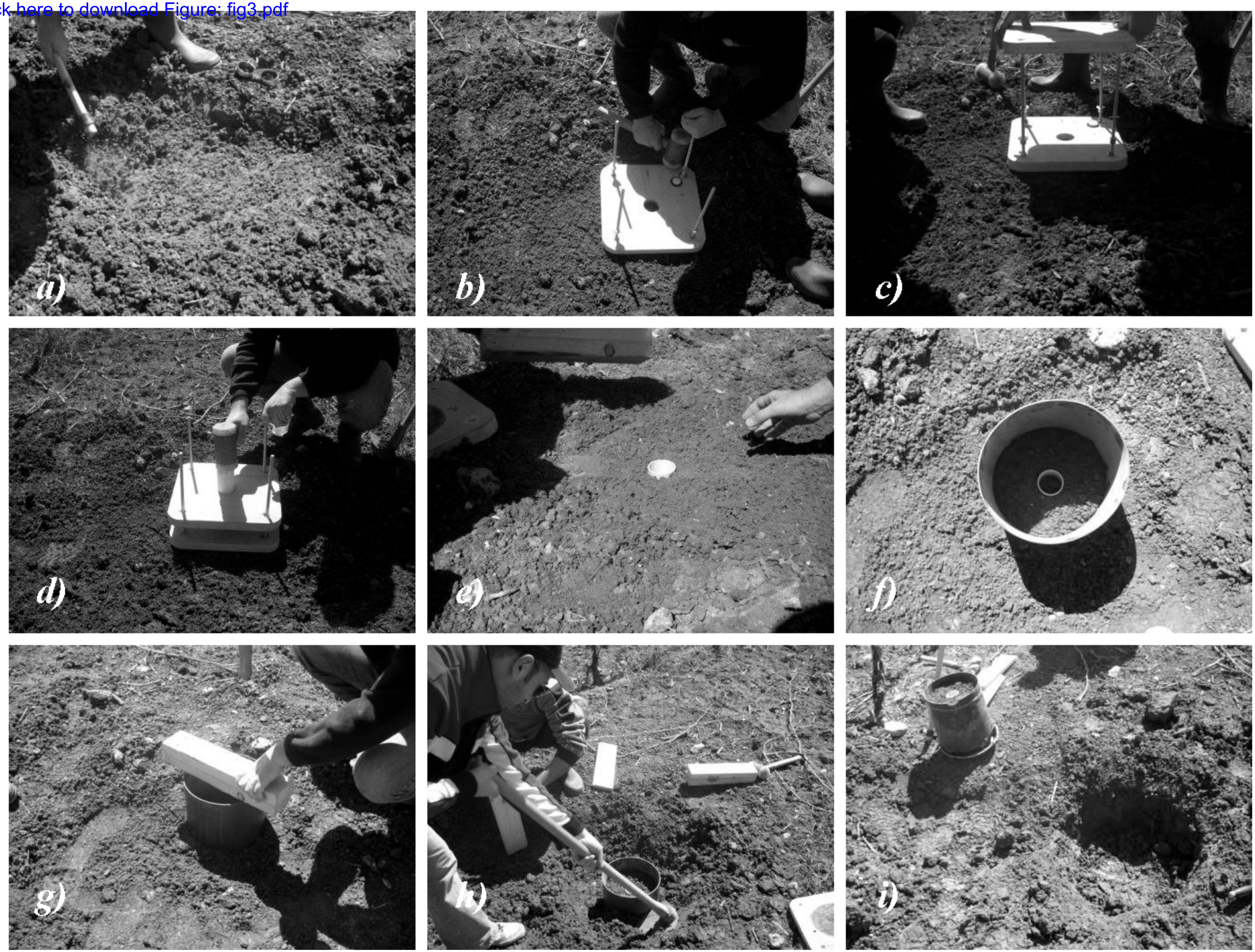

Fig4

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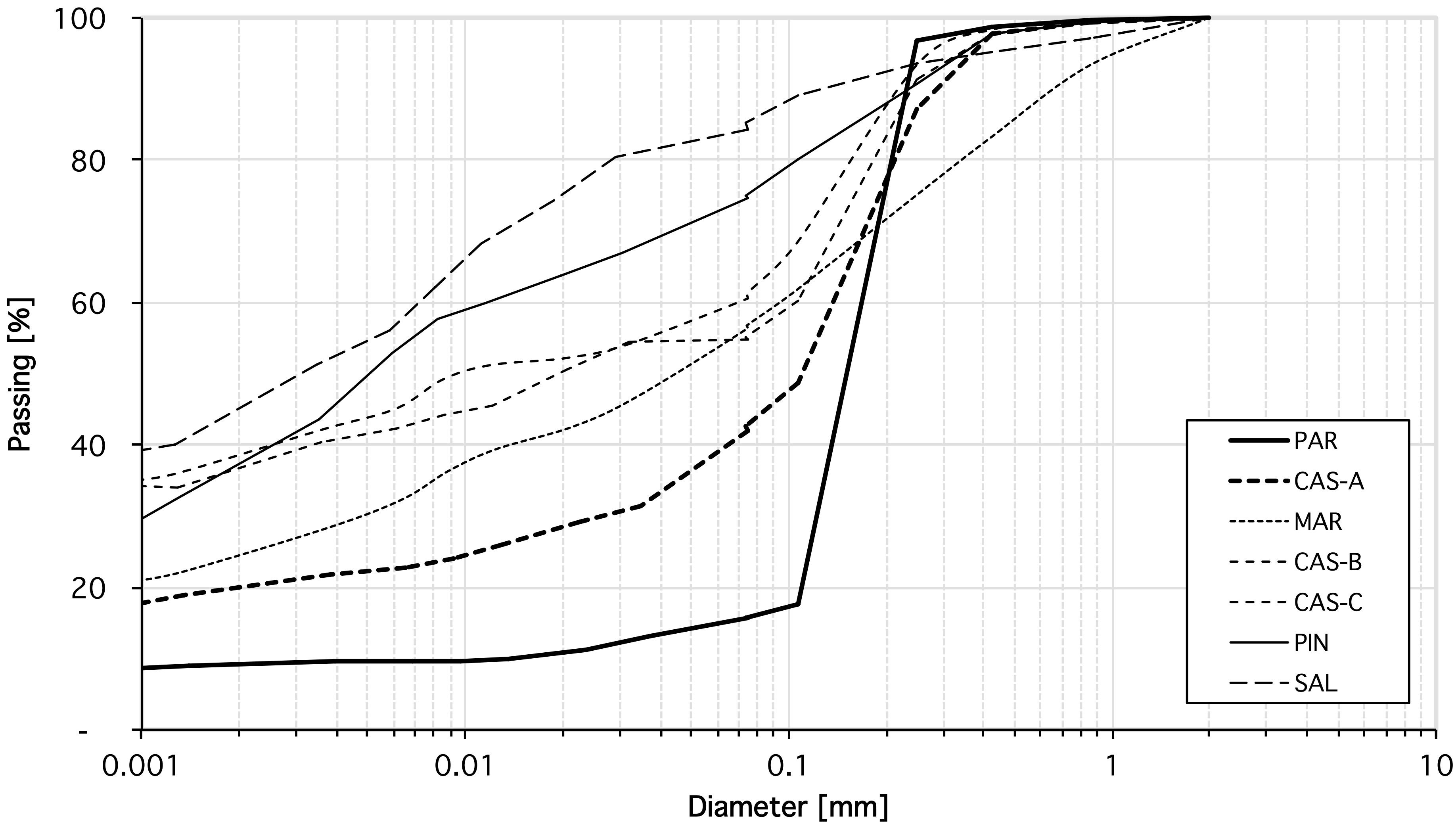

Fig5

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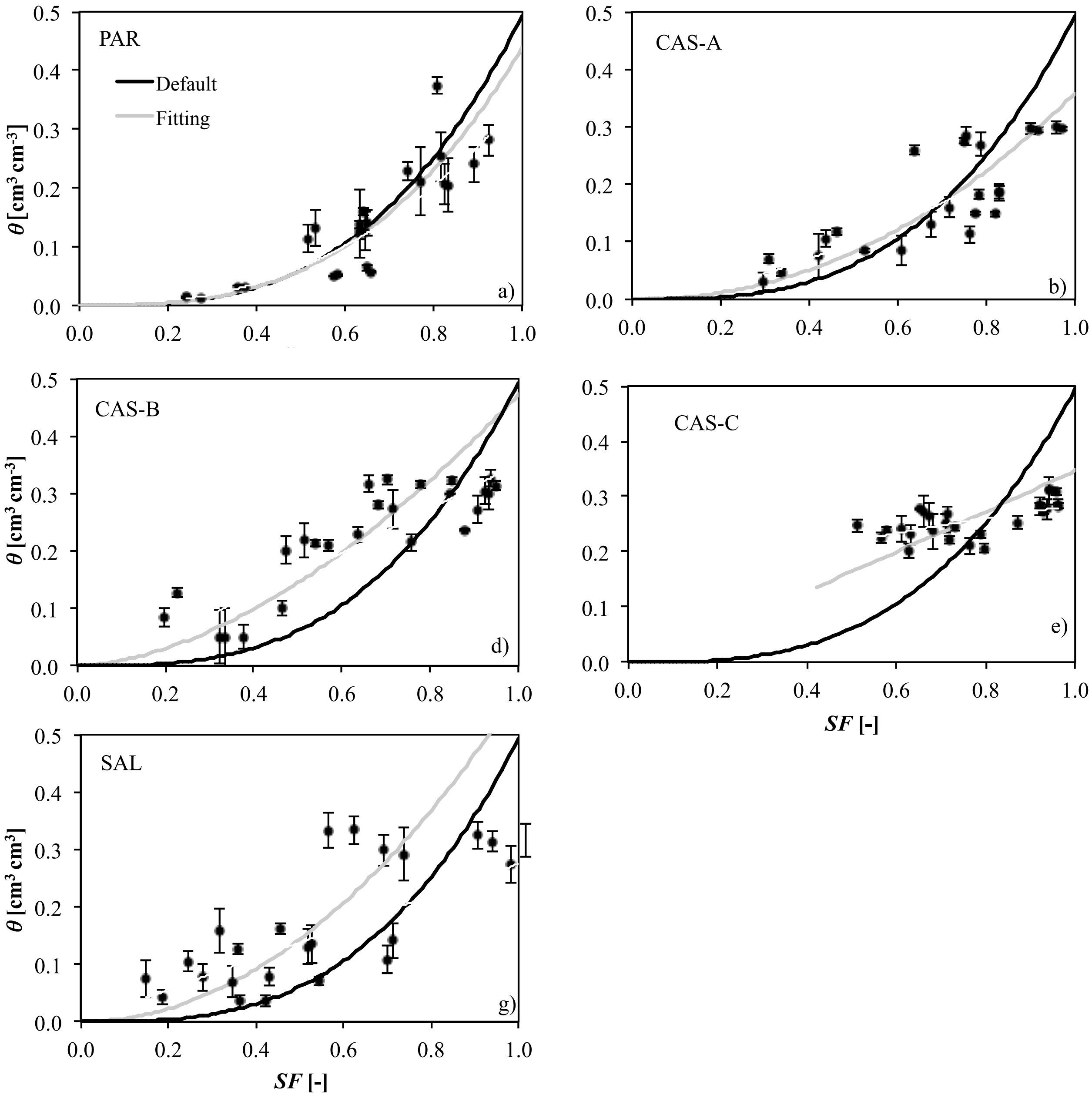

Fig6

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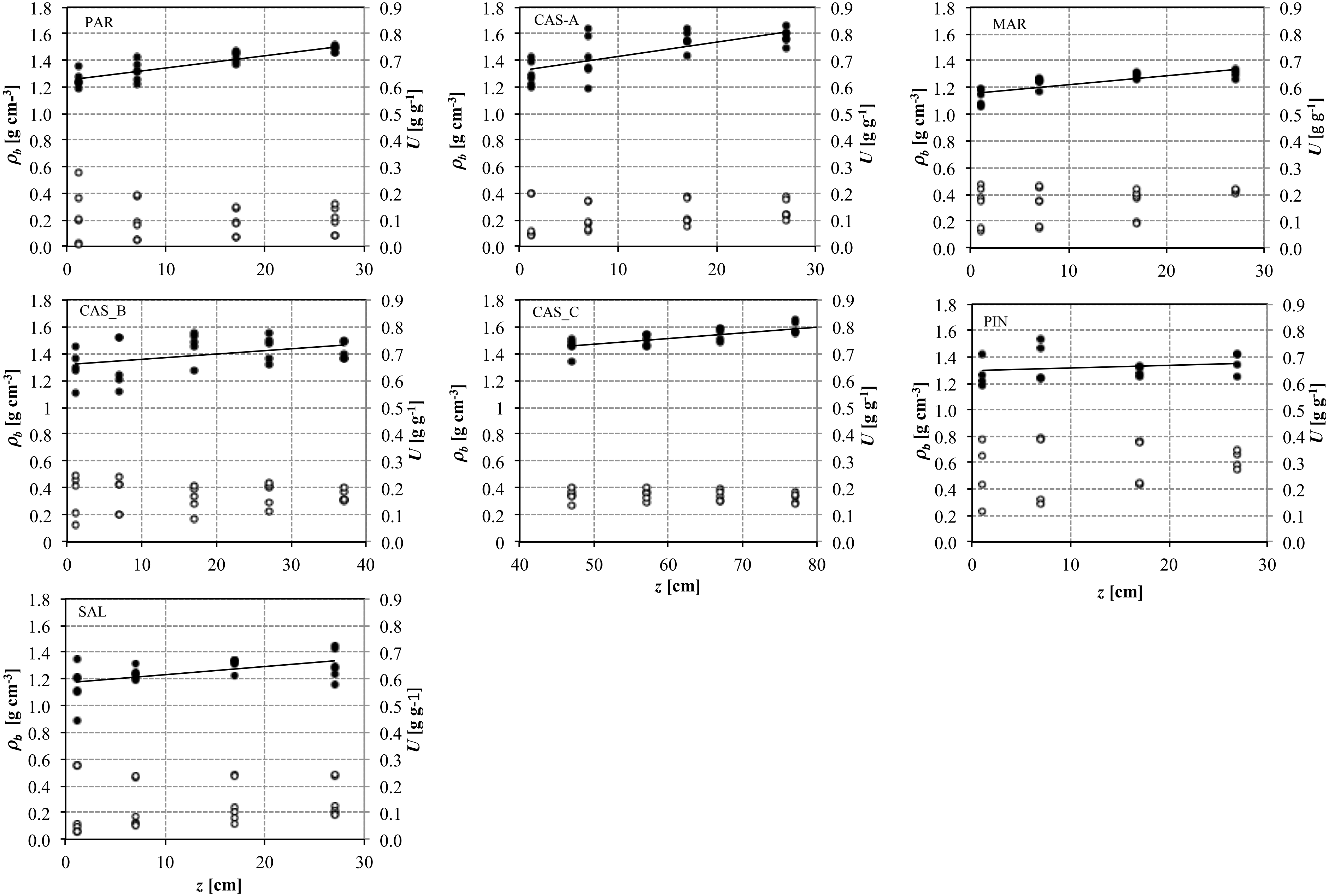

Fig7

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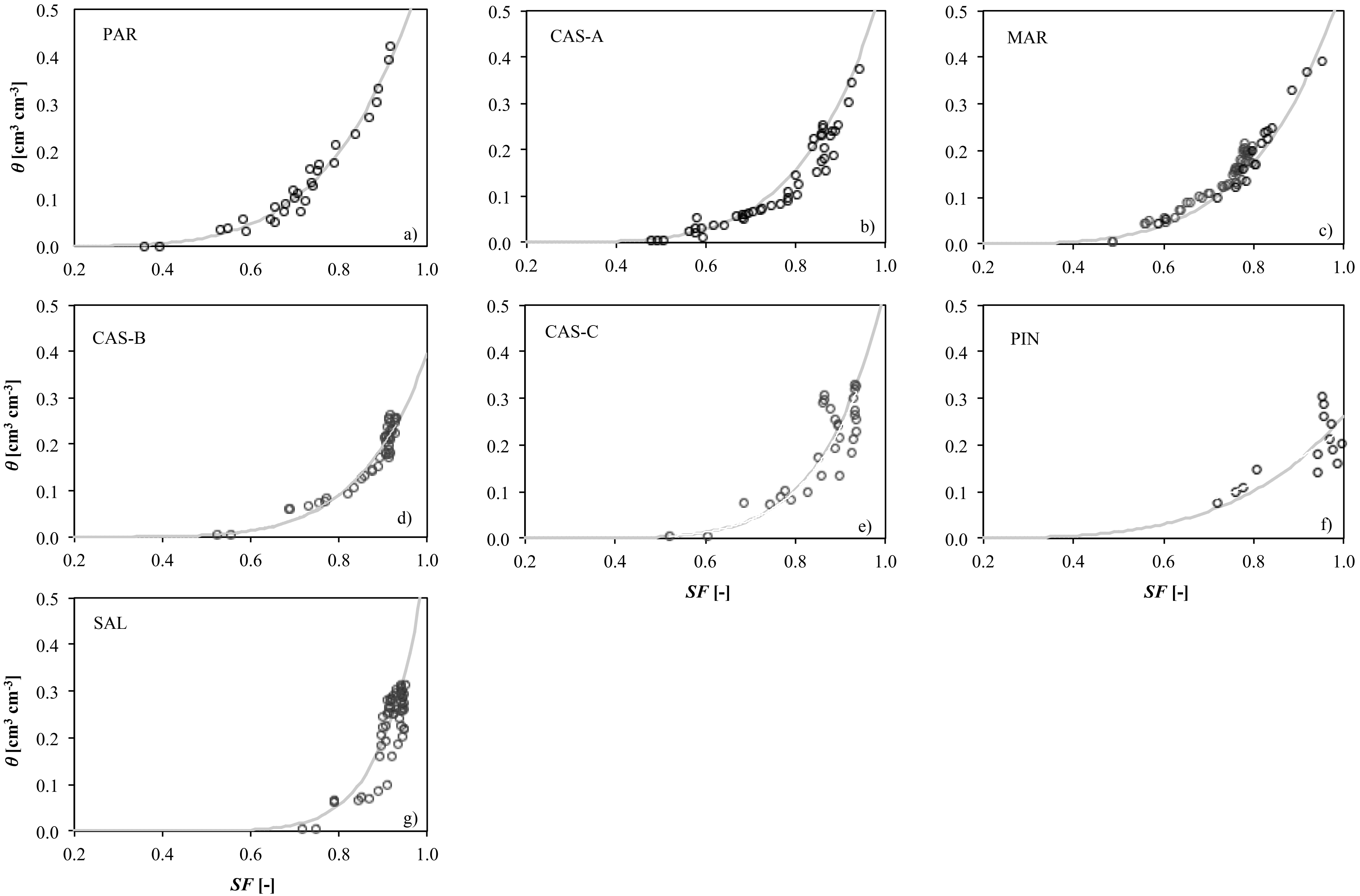

Fig8

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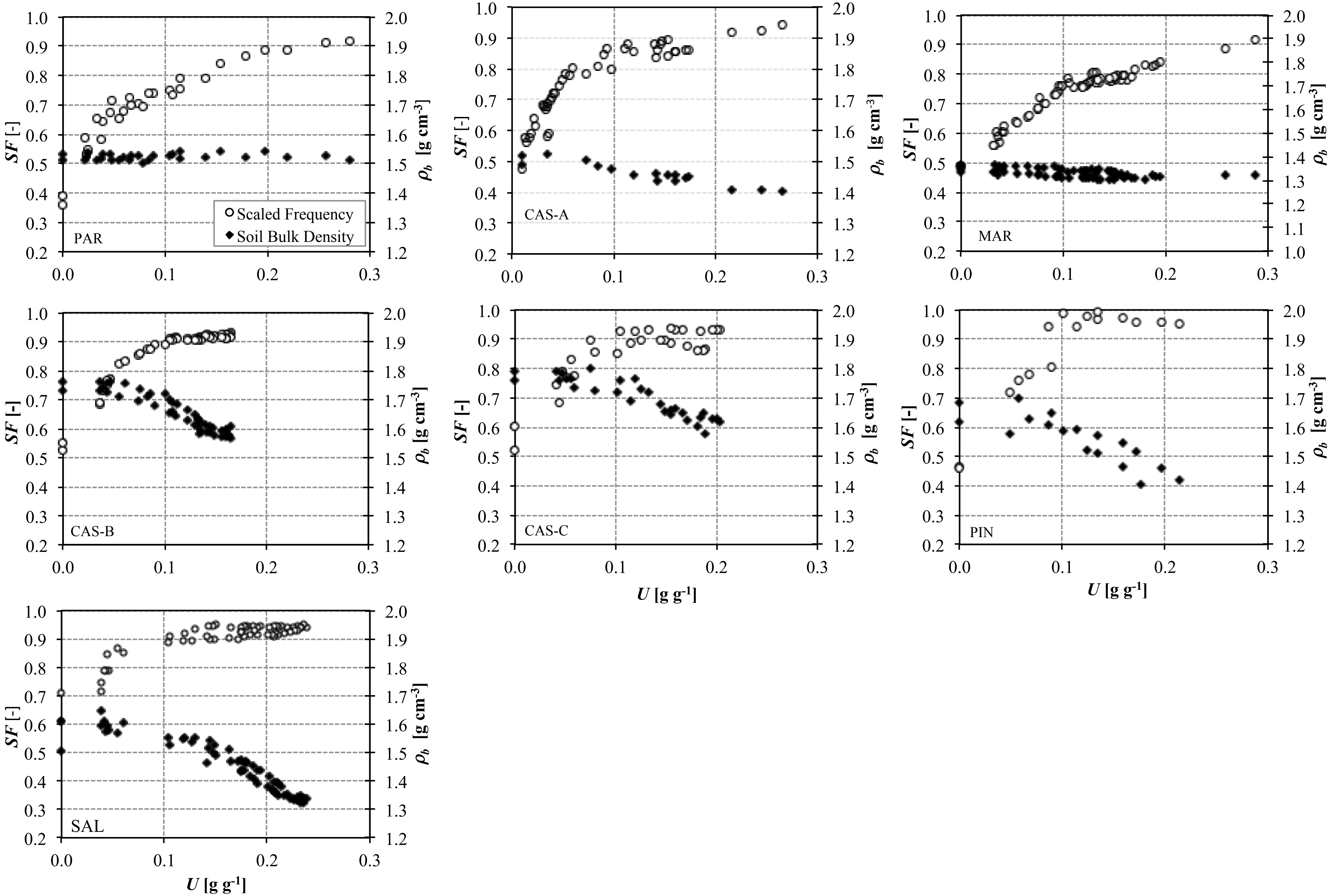

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